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Minimal dynamical inverse seesaw mechanism

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We present a minimal model in which the inverse see saw is realized dynamically. The two unity lepton number-breaking term is induced at two-loop level and is naturally around the keV scale, while right-handed neutrinos are at the TeV scale. An interesting extension of the model is obtained by gauging $B - L$: in this case, anomaly cancellation has as a direct consequence the presence of a sterile neutrino at the MeV scale that may be a good dark matter candidate. Moreover, the new gauge boson Z' and the new neutral scalars may have characteristic signatures at LHC.

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I. INTRODUCTION

Experimental evidence of “tiny” neutrino masses [1] has motivated the development of a plethora of mechanisms that may explain their growth and their smallness with respect to the other standard model (SM) fermion masses. Definitely the best known mechanism is the see saw (SS) mechanism, usually called type I SS [2] that ascribes to a very high new physics scale. Unfortunately, if nature had chosen type I SS, we would not have any hope to confirm it at Large Hadron Collider (LHC) experiments.

Among all the mechanisms that provide neutrino masses, a very interesting possibility is the so called inverse see saw (ISS) mechanism [3,4]. In this scheme, no new physics above the TeV scale is introduced, and the smallness of neutrino masses is justified by the smallness of a parameter that breaks the lepton number by two unity, namely μ . In the limit in which this parameter goes to zero, the lepton number is restored and neutrinos are massless. Being the new physics scale around the TeV, this model is quite appealing for LHC searches. Still, the community has always shown a sizable skepticism against this mechanism due to the difficulty in justifying the μ smallness. It is fair to say that the μ smallness is not a problem as long as one accepts that very small parameters, majorana masses, or Yukawa couplings, are natural. If we assume that natural adimensional parameters should be of order one, and dimensional parameters of order the electroweak (EW) scale for a TeV cutoff, this is not true anymore. Here, we assume this point of view.¹ Whereas, in the original formulation of the model, this was ascribed to superstring inspired E_6 scenario [3], recently an attempt has been done in the supersymmetric ISS [5], where the smallness of μ was related to vanishing trilinear susy soft terms at the grand unified theory (GUT) scale. Renormalization group equations (RGEs) both induced them and furnished a dynamical

mechanism to justify the μ size. However, this mechanism had to appeal to a string inspired scenario that could provide vanishing trilinear terms at the GUT scale. So far, a very appealing picture is the radiative origin of the two unity lepton number-breaking parameter as it has been proposed in [6]: it is induced at two-loop level, thus explaining its smallness with respect to the electroweak scale (EW). However, in [6], an $SO(10)$ inspired approach is used, hence implying the presence of many new degrees of freedom.

Here, we use a bottom-top approach, building the dynamical ISS step by step to satisfy the criteria of *naturalness* and *minimality*: we reject *ad hoc* fine tuning in the potential parameters and we look for the minimal set of ingredients needed to allow the mechanism to work. For this reason, we start dealing with the global lepton number without introducing extra fermions with respect to the usual ISS model but only new scalar fields. From this point of view, the model proposed is quite different from [6], where the new fermions play a crucial role in the loops that generate the two unity lepton number-breaking terms.

The paper is organized in this way: the Sec. II of the paper revises the ISS idea and explains the main difficulties in generating dynamically the μ term preserving naturalness. Section III describes the mechanism proposed, while the Sec. IV sketches an appealing extension obtained by gauging $B - L$. The latter formulation is less minimal but more phenomenologically interesting. Moreover, it has the nice feature to have a MeV Dark Matter (DM) candidate.

II. TOWARDS A DYNAMICAL ISS REALIZATION: NATURALNESS PROBLEM

In this section, we briefly review the ISS mechanism and present the problems related to its dynamical version.

The ISS model is realized by adding to the SM field content two kind of sterile fermions, the usual right-handed neutrino, ν^c , and a new singlet S , charged under lepton number -1 and 1 , respectively. The lagrangian is invariant under the lepton number except for a very tiny majorana mass term, μ , involving the new singlet S . Because of their

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¹Clearly, in this context, also first and second charged fermion generation Yukawa couplings should be justified in a dynamical way. However, these issues go beyond the purposes of this paper.

singlet nature and lepton charges, ν^c and S share a Dirac mass term, M . The Yukawa lagrangian relevant for neutrino masses is given by

$$\mathcal{L} = y_\nu L h \nu^c + M \nu^c S + \frac{1}{2} \mu S S + \text{H.c.}, \quad (1)$$

where L is the $SU(2)$ lepton doublet, h the standard higgs doublet, and for simplicity, we consider only one lepton generation.

When the EW symmetry is broken by the Higgs vacuum expectation value (VEV) $\langle h \rangle = v_W/\sqrt{2}$, the neutrino Dirac mass term $m_D = y_\nu v_W/\sqrt{2}$ is generated. In the basis (ν_L, ν^c, S) the neutrino mass matrix is given by

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{pmatrix}, \quad (2)$$

and a tiny neutrino mass is generated

$$m_\nu \sim \mu \frac{m_D^2}{M^2}. \quad (3)$$

Clearly, since m_D is fixed around the EW scale ~ 100 GeV and $|m_\nu| \leq \text{eV}$, μ and M are related and

$$M \geq \sqrt{(\mu/\text{keV})\sqrt{10}} \text{ TeV}; \quad (4)$$

thus, for $\mu \sim \mathcal{O}(\text{keV})$, the singlet neutrino mass is around the TeV scale, making the model more phenomenologically interesting with respect to the high energy SS realizations.

In order to generate μ dynamically, we could think that the lepton number is spontaneously broken by the VEV of a SM singlet Δ with lepton number -2 . Since $\mu \sim \langle \Delta \rangle$, we should furnish an argument to justify why $\langle \Delta \rangle \sim \text{keV}$ whereas the natural scale is the EW one.

Indeed, if we add at the ISS field content a SM singlet Δ with lepton number -2 , and assume that the lagrangian is lepton number invariant, the Yukawa lagrangian in Eq. (1) is replaced by

$$\mathcal{L} = y_\nu L H \nu^c + M \nu^c S + \frac{1}{2} y_S \Delta S S + \frac{1}{2} y_{\nu^c} \Delta^\dagger \nu^c \nu^c + \text{H.c.}, \quad (5)$$

yielding to a neutrino mass matrix

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & \tilde{\mu} & M \\ 0 & M & \mu \end{pmatrix}, \quad (6)$$

with $\tilde{\mu} \sim \mu$. However, $\tilde{\mu}$ enters in the light neutrino masses only at next to leading order. Using the block diagonalization method introduced by [7], it is easy to see that the light neutrino mass is still given by

$$m_\nu \sim \mu \frac{m_D^2}{M^2}, \quad (7)$$

while the two heavy states have masses

$$\pm \left(M + \frac{m_D^2}{2M} \right) + \frac{1}{2} (\mu + \tilde{\mu}) - \mu \frac{m_D^2}{2M^2}. \quad (8)$$

This may be easily understood by looking at the Feynman diagram in Fig. 1, where it is clear that $\tilde{\mu}$ enters only at the second order level.

In the presence of the new singlet Δ , the lepton number—and SM gauge symmetries—scalar invariant potential is given by

$$V[h, \Delta] = \mu_h^2 (h^\dagger h) + \mu_\Delta^2 (\Delta^\dagger \Delta) + \lambda_h (h^\dagger h)^2 + \lambda_\Delta (\Delta^\dagger \Delta)^2 + \lambda_{h\Delta} (h^\dagger h) (\Delta^\dagger \Delta). \quad (9)$$

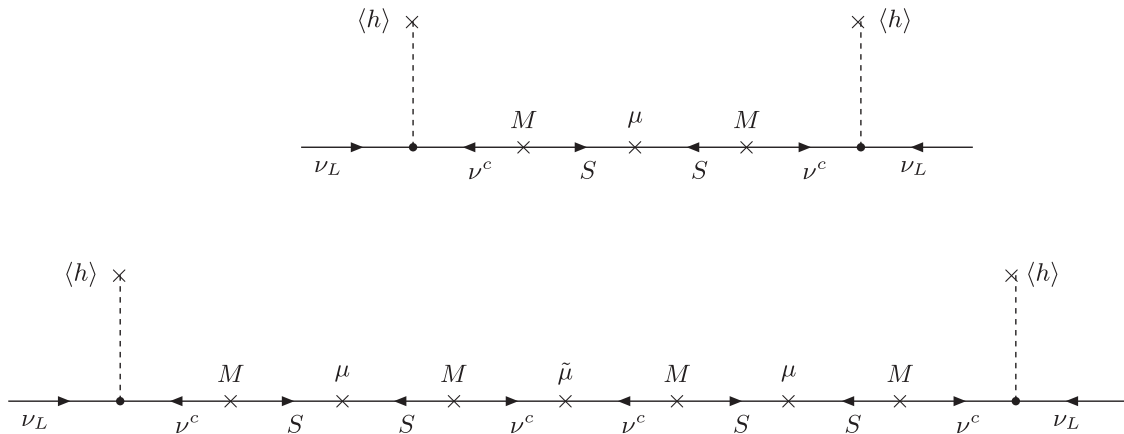


FIG. 1. The origin of neutrino masses in the ISS model where both the μ and $\tilde{\mu}$ terms are present. The contribution proportional to $\tilde{\mu}$ is subleading.

By imposing the vacuum configuration

$$\langle h \rangle = v_W/\sqrt{2}, \quad \langle \Delta \rangle = v_\Delta, \quad (10)$$

the minimum equations give:

$$\frac{v_W^2}{2} = \frac{2\lambda_\Delta \mu_h^2 - \lambda_{h\Delta} \mu_\Delta^2}{\lambda_{h\Delta}^2 - 4\lambda_h \lambda_\Delta} \quad v_\Delta^2 = \frac{2\lambda_h \mu_\Delta^2 - \lambda_{h\Delta} \mu_h^2}{\lambda_{h\Delta}^2 - 4\lambda_h \lambda_\Delta}. \quad (11)$$

From Eq. (11), we see that since $v_W = 246$ GeV, $v_\Delta \sim$ keV may be obtained only by admitting a fine tuning of order $\sim 10^{-12}$. Moreover, even by allowing such a fine tuning, the breaking of the continuous lepton number gives rise to a Goldstone boson (GB), the so called Majoron, that interacts with neutrinos through a coupling $m_\nu/v_\Delta \sim y_S m_D^2/M^2 \sim 10^{-3}$. Bounds on neutrino-Majoron coupling are obtained by no-observation of $\beta\beta$ -decays and in pion and kaon decay experiments [8–10]. Nevertheless, the strongest bounds are obtained by analyzing supernova explosion [11] and cosmic microwave background (CMB) [12]. All these analyses have been performed taking into account the 3 SM lepton generations, but for our purposes we may take as reference value the bound indicated for the diagonal couplings, $g \leq 10^{-7}$, with the off-diagonal ones being even more restrictive. The present bound is 4 order of magnitude smaller than the value expected in the ISS formulation so far sketched, hence ruling it out.

The simplest way to solve such a scheme would be to allow smaller values for y_S that would automatically turn into larger values for v_Δ , thus both relaxing the fine tuning problem and solving the Majoron one. However, this would require a very small Yukawa coupling that, in our context, is considered not natural. The scheme may also be saved by assuming that lepton number is explicitly softly broken, thus avoiding the problem of the massless Majoron. Nevertheless, the naturalness problem would not be solved, thus requiring looking for alternative solutions.

Furthermore, it should be noticed that in this scheme, we could not gauge the global lepton number because the new gauge boson would be too light and automatically excluded by LEP analysis [13,14].

Let us now suppose that lepton number is spontaneously broken by the VEV of a SM singlet $\tilde{\Delta}$ with lepton charge -1 and $\langle \tilde{\Delta} \rangle \sim v_W$. To implement the ISS, we would need an *hidden* sector that gives rise to the effective operator

$$y_S \frac{\tilde{\Delta}^2}{\Lambda_{\text{eff}}} \text{SS}, \quad (12)$$

where Λ_{eff} is an effective scale that should be $\sim \langle \tilde{\Delta} \rangle^2/\mu \sim v_W^2/\mu \sim 10^7$ TeV. Clearly, this operator may be originated by integrating out heavy fermions with a mass around 10^7 TeV, but this would shift the cutoff of our model to $\sim 10^8$ TeV, thus reintroducing a new tension between the TeV sterile neutrinos scale and this new cutoff.² On the other hand, this operator could be originated at the loop level: in this case we may write $1/\Lambda_{\text{eff}}$ as

$$\frac{1}{\Lambda_{\text{eff}}} = c \left(\frac{1}{16\pi^2} \right)^n \frac{1}{\Lambda}, \quad (13)$$

where n is the number of loops, c summarizes the product of different factors and couplings that enter in the loops and Λ may now be taken between 1 and 10 TeV. For $c \sim 0.1$ –1 we need $n = 2$ –3 to sufficiently suppress the effective operator.

In the following section, we will show a minimal SM extension that implements this structure.

III. THE MECHANISM

At the SM field content, we add the ISS model sterile fermion content, ν^c and S , and 3 new scalar SM singlets: a real scalar field ϕ , uncharged under the lepton number, and two complex fields $\tilde{\Delta}$ and Δ with lepton charges -1 and -2 respectively. The Yukawa lagrangian involving the new fields coincides with the one given in Eq. (5)

$$\mathcal{L} = y_\nu L H \nu^c + M \nu^c S + \frac{1}{2} y_S \Delta S S + \frac{1}{2} y_{\nu^c} \Delta^\dagger \nu^c \nu^c, \quad (14)$$

while the SM scalar potential is modified to

$$V[h, \phi, \tilde{\Delta}, \Delta] = V_h + V_{\text{sing}} + V_{h \text{ sing}}, \quad (15)$$

where

$$\begin{aligned} V_h &= \mu_h^2 (h^\dagger h) + \lambda_h (h^\dagger h)^2; \\ V_{\text{sing}} &= k\phi + \mu_\phi^2 \phi^2 + A_\phi \phi^3 + \lambda_\phi \phi^4 + \mu_{\tilde{\Delta}}^2 (\tilde{\Delta}^\dagger \tilde{\Delta}) + \mu_\Delta^2 (\Delta^\dagger \Delta) + A_{\tilde{\Delta}} \phi (\tilde{\Delta}^\dagger \tilde{\Delta}) + A_\Delta \phi (\Delta^\dagger \Delta) + (\lambda e^{i\alpha} \tilde{\Delta}^{\dagger 2} \Delta + \text{H.c.}) \\ &\quad + (B e^{i\beta} \phi \tilde{\Delta}^{\dagger 2} \Delta + \text{H.c.}) + \lambda_{\tilde{\Delta}} (\tilde{\Delta}^\dagger \tilde{\Delta})^2 + \lambda_\Delta (\Delta^\dagger \Delta)^2 + \lambda_{\tilde{\Delta}\phi} \phi^2 (\tilde{\Delta}^\dagger \tilde{\Delta}) + \lambda_{\Delta\phi} \phi^2 (\Delta^\dagger \Delta) + \lambda_{\Delta\tilde{\Delta}} (\Delta^\dagger \Delta) (\tilde{\Delta}^\dagger \tilde{\Delta}); \\ V_{h \text{ sing}} &= A_h \phi (h^\dagger h) + \lambda_{h\phi} \phi^2 (h^\dagger h) + \lambda_{h\tilde{\Delta}} (h^\dagger h) (\tilde{\Delta}^\dagger \tilde{\Delta}) + \lambda_{h\Delta} (h^\dagger h) (\Delta^\dagger \Delta). \end{aligned} \quad (16)$$

²In μ , the μ smallness is justified in coming from a higher dimensional operator. However, in that context such higher order operator is obtained by explicitly breaking the lepton number. Here we are interested in lepton number spontaneous breaking.

The mechanism we are proposing works if

- (1) Δ is inert and does not develop a VEV;
- (2) all the neutral real components of the scalar fields mix. This mixing would induce the μ term given in Eq. (6) at the two-loop level.

Consider the first derivative system given by

$$\frac{\partial V[h, \phi, \tilde{\Delta}, \Delta]}{\partial \varphi_i^\alpha} = 0, \quad (17)$$

where $\varphi = (h, \phi, \tilde{\Delta}, \Delta)$ and α runs on all the scalar components of the field φ_i . The vacuum configuration given by

$$\langle h \rangle = v_W / \sqrt{2} \quad \langle \phi \rangle = v_\phi \quad \langle \tilde{\Delta} \rangle = v_{\tilde{\Delta}} / \sqrt{2} \quad \langle \Delta \rangle = 0 \quad (18)$$

is a minimum of the scalar potential when

$$\begin{aligned} \beta &= \alpha + \pi, & B &= -\frac{\lambda}{v_\phi}, \\ \mu_h^2 &= -\frac{1}{2}(2A_h + 2\lambda_{h\phi}v_\phi^2 + \lambda_{h\tilde{\Delta}}v_{\tilde{\Delta}}^2 + 2\lambda_h v_W^2), \\ \mu_\phi^2 &= -\frac{1}{4v_\phi}(2k + A_\phi v_W^2 + A_{\tilde{\Delta}}v_{\tilde{\Delta}}^2 + 2A_\phi v_\phi^2 \\ &\quad + 2\lambda_{\tilde{\Delta}\phi}v_{\tilde{\Delta}}^2 v_\phi + 2\lambda_{h\phi}v_W^2 v_\phi + 2\lambda_\phi v_\phi^3), \\ \mu_{\tilde{\Delta}}^2 &= -\frac{1}{2}(2A_{\tilde{\Delta}}v_\phi + 2\lambda_{\tilde{\Delta}\phi}v_\phi^2 + 2\lambda_{\tilde{\Delta}\phi}v_\phi^2 \\ &\quad + \lambda_{h\tilde{\Delta}}v_W^2 + 2\lambda_{\tilde{\Delta}}v_{\tilde{\Delta}}^2). \end{aligned} \quad (19)$$

$$M_0^2 = \begin{pmatrix} 2\lambda_h v_W^2 & A_h v_W + 2\lambda_{h\phi} v_\phi v_W & \lambda_{h\tilde{\Delta}} v_W v_{\tilde{\Delta}} & 0 \\ A_h v_W + 2\lambda_{h\phi} v_\phi v_W & -\frac{1}{2v_\phi}(2k + A_\phi v_W^2 + A_{\tilde{\Delta}}v_{\tilde{\Delta}}^2 + 2A_\phi v_\phi^2 + 2\lambda_{h\phi}v_W^2 v_\phi + 4\lambda_\phi v_\phi^3) & A_{\tilde{\Delta}}v_{\tilde{\Delta}} + 2\lambda_{\tilde{\Delta}\phi}v_\phi v_{\tilde{\Delta}} & -\frac{\lambda \cos \alpha v_{\tilde{\Delta}}^2}{\sqrt{2}v_\phi} \\ \lambda_{h\tilde{\Delta}} v_W v_{\tilde{\Delta}} & A_{\tilde{\Delta}}v_{\tilde{\Delta}} + 2\lambda_{\tilde{\Delta}\phi}v_\phi v_{\tilde{\Delta}} & 2\lambda_{\tilde{\Delta}}v_{\tilde{\Delta}}^2 & 0 \\ 0 & -\frac{\lambda \cos \alpha v_{\tilde{\Delta}}^2}{\sqrt{2}v_\phi} & 0 & m_a^2 \end{pmatrix}, \quad (21)$$

where m_a^2 is given in Eq. (20) and the mass matrix M_0^2 is written in the basis $(h, \phi, \tilde{\Delta}, \Delta)$. M_0^2 has a nonvanishing determinant; thus, we do not have additional massless particles.

The μ term is induced at the two-loop level thanks to the mixing of the 4 neutral CP even states as may be seen in Fig. 2. The presence of the singlet ϕ is fundamental in order to allow the vacuum configuration given in Eq. (18): without ϕ , Δ could not behave as an inert scalar thus destroying the full mechanism.

The μ term expression is roughly given

$$\begin{aligned} \mu &\sim y_S^2 y_{\nu^c} \frac{1}{(16\pi^2)^2} A^3 \frac{v_{\tilde{\Delta}}^2}{M^4} \sim y_S^2 y_{\nu^c} 10^{-5} \frac{v_W^5}{(1 \text{ TeV})^4} \\ &\sim y_S^2 y_{\nu^c} 10^{-5} \text{ GeV} \sim y_S^2 y_{\nu^c} 10 \text{ keV} \sim 1 \text{ keV}, \end{aligned} \quad (22)$$

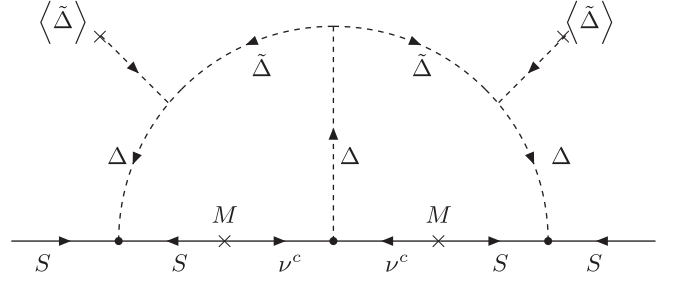


FIG. 2. Radiative correction that induces the $\hat{\nu}_2^c$ mass $\sim \text{MeV}$.

The imaginary part of $\tilde{\Delta}$ gives rise to the massless Majoron, while the imaginary part of Δ to a CP odd neutral state a with mass

$$m_a^2 = \mu_{\tilde{\Delta}}^2 + A_{\tilde{\Delta}}v_\phi + \lambda_{\Delta\phi}v_\phi^2 + \frac{1}{2}\lambda_{\Delta\tilde{\Delta}}v_{\tilde{\Delta}}^2 + \frac{1}{2}\lambda_{h\Delta}v_W^2. \quad (20)$$

Among the 4 components of the SM Higgs doublet, 3 corresponds to the GBs eaten by the SM gauge bosons, while the neutral CP even component mixes with the neutral CP even components of the SM singlets through

where $A^3 \sim v_W^3$ stays for the product of scalar potential trilinear couplings and we have assumed $y_S, y_{\nu^c} < 1$.

To be noticed that in this scheme the neutrino-Majoron coupling y_J is sufficiently suppressed to satisfy all the constraints [11,12]

$$y_J \sim \frac{m_\nu}{v_{\tilde{\Delta}}} \sim 10^{-11}. \quad (23)$$

IV. OUTLOOK: GAUGED $B - L$ NUMBER IN THE DYNAMICAL ISS SCENARIO

In the previous section, we have provided a mechanism that furnishes a justification for the keV scale of the ISS model. Furthermore, the associated Majoron is sufficiently weakly coupled to neutrinos not to be ruled out by the most recent analysis.

Nevertheless, we may ask what could change in the gauged version of the mechanism proposed. In this section we will briefly sketch the main features of the gauge version of the model so far described, leaving for a future work the detailed analysis.

Once the lepton number is gauged, in order to erase the triangle anomalies of the kind $SU(2) - SU(2) - U(1)_L$ and $U(1)_Y - U(1)_Y - U(1)_L$, where $SU(2)$ and $U(1)_Y$ are the EW SM symmetries and $U(1)_L$ is the lepton symmetry, we are forced to gauge the global symmetry $U(1)_{B-L}$ and not only $U(1)_L$. So far, nothing changes for what concerns neutrino masses and the scalar potential discussion. However, due to the presence of the singlet S , a triangle anomaly is still left that relates to the triangle $U(1)_{B-L} - U(1)_{B-L} - U(1)_{B-L}$. In our ISS scheme, we may get an anomaly free $U(1)_{B-L}$ by adding one right-handed neutrino ν_1^c for each generation and another right-handed neutrino ν_2^c for each singlet S .³ In this case, the neutrino Yukawa lagrangian in Eq. (14) becomes

$$\begin{aligned} \mathcal{L} = & y_{\nu_1} LH \nu_1^c + y_{\nu_2} LH \nu_2^c + M_1 \nu_1^c S + M_2 \nu_2^c S \\ & + 1/2 y_S \Delta S S + 1/2 y_{\nu_1^a} \Delta^\dagger \nu_1^c \nu_1^c + 1/2 y_{\nu_2^a} \Delta^\dagger \nu_2^c \nu_2^c \\ & + y_{\nu^b} \Delta^\dagger \nu_1^c \nu_2^c + \text{H.c.}, \end{aligned} \quad (24)$$

and after EW and lepton number spontaneous breaking the neutrino mass matrix given in Eq. (6) turns into

$$M_\nu = \begin{pmatrix} 0 & m_{D_1} & m_{D_2} & 0 \\ m_{D_1} & \tilde{\mu}_1 & \tilde{m} & M_1 \\ m_{D_2} & \tilde{m} & \tilde{\mu}_2 & M_2 \\ 0 & M_1 & M_2 & \mu \end{pmatrix} \sim \begin{pmatrix} 0 & m_{D_1} & m_{D_2} & 0 \\ m_{D_1} & 0 & 0 & M_1 \\ m_{D_2} & 0 & 0 & M_2 \\ 0 & M_1 & M_2 & 0 \end{pmatrix}, \quad (25)$$

since $\mu, \tilde{\mu}_{1,2}, \tilde{m} \ll m_{D_{1,2}} \ll M$.⁴ To prevent that left-handed neutrinos participate to a GeV scale Dirac neutrino, we need to impose a permutation matter symmetry between ν_1^c and ν_2^c . In this way, $y_{\nu_1} = y_{\nu_2} = y_\nu, M_1 = M_2 = M$, and $y_{\nu_1^a} = y_{\nu_2^a} = y_{\nu^a}$. Defining the right-handed neutrino basis

$$\hat{\nu}_1^c = \frac{1}{\sqrt{2}}(\nu_1^c + \nu_2^c), \quad \hat{\nu}_2^c = \frac{1}{\sqrt{2}}(-\nu_1^c + \nu_2^c), \quad (26)$$

Equation (24) becomes

$$\begin{aligned} \mathcal{L} = & y_\nu \sqrt{2} LH \hat{\nu}_1^c + \sqrt{2} M \hat{\nu}_1^c S + 1/2 y_S \Delta S S \\ & + 1/2 (y_{\nu^a} + y_{\nu^b}) \Delta^\dagger \hat{\nu}_1^c \hat{\nu}_1^c \\ & + 1/2 (y_{\nu^a} - y_{\nu^b}) \Delta^\dagger \hat{\nu}_2^c \hat{\nu}_2^c + \text{H.c.} \end{aligned} \quad (27)$$

³Here, we consider the case of only one generation.

⁴ $\mu, \tilde{\mu}_{1,2}, \tilde{m}$ would be all induced at the two-loop level.

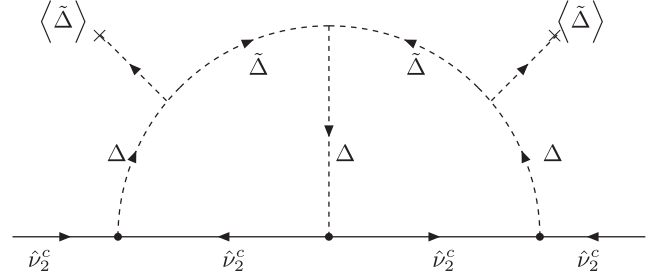


FIG. 3. Radiative correction that induces the $\hat{\nu}_2^c$ mass $\sim \text{MeV}$.

Clearly, in this basis the permutation symmetry is now a Z_2 -matter symmetry, under which $\hat{\nu}_2^c$ is odd while $\hat{\nu}_1^c$ is even, as all the other fermion and scalar particles. Light neutrino masses are induced as in the previous formulation, and only $\hat{\nu}_1^c$ participates in the ISS mechanism. On the other hand, $\hat{\nu}_2^c$ is a sterile neutrino decoupled by all the other fermions whose mass is generated at the two-loop level as it happens for the μ term. However, the radiative correction for \hat{m}_2 is slightly different with respect to the one that gives rise to μ , as may be seen by looking at Fig. 3: $\hat{\nu}_2^c$ does not participate in a quasi-Dirac spinor and therefore only $\hat{\nu}_2^c$ runs in the loops. As consequence,

$$\hat{m}_2 \sim \hat{y}_\nu^3 \frac{1}{(16\pi^2)^2} \frac{A^3}{m_S^2} \sim \hat{y}_\nu^3 10^{-5} v_W \sim 0.1-1 \text{ MeV}, \quad (28)$$

where $A^3 \sim v_W^3$, as in Eq. (22), m_S stays for the generic scalar mass of the fields in the loops and $\hat{y}_\nu = 1/2(y_{\nu^a} - y_{\nu^b})$.

In this case, we have found a very nice link between the μ term in the ISS model and the presence of a MeV sterile neutrino. This sterile neutrino interacts weakly with the new gauge boson Z' and with the new singlet sector through its coupling with Δ ; and, it is stable because of the Z_2 symmetry, thus it is a possible MeV DM candidate. The scenario underlined is similar to that proposed in [16], even if in that case the model was supersymmetric. The full analysis of this candidate as plausible DM will be addressed in a following paper [17].

The phenomenology of the model in its gauged formulation is much more interesting: the new Z' may be produced at LHC and then detected through the usual $U(1)_{B-L}$ channels [14,18] or through its decays into the new neutral scalar sector, thus giving rise to specific signatures. Even these aspects will be addressed afterwards [17].

V. CONCLUSION

The ISS mechanism is one of the most appealing mechanisms introduced to explain neutrino masses: lepton number is almost an approximate symmetry of the lagrangian, being broken by a very small mass term in a new fermion

sector. The presence of the lepton number-breaking parameter induces tiny left-handed neutrino masses that vanish when the lepton symmetry is restored. Although one may invoke t'Hooft's criteria [19] to justify the smallness of μ , the criteria does not provide an explanation, notwithstanding the original ISS model.

In this paper, we have proposed a minimal model in which the two unity lepton number-breaking parameter is induced at the two-loop level. The model has been built following the two criteria of *naturalness* and *minimality*. The new physics scale is around the TeV and the lepton number-breaking scale is comparable to the EW one. The simplest version of the model has a reduced number of new degrees of freedom with respect to the usual ISS model: three SM scalar singlets: ϕ , $\tilde{\Delta}$, and Δ with lepton charges 0, -1 , and -2 , respectively. Δ is inert while ϕ and $\tilde{\Delta}$ develop a VEV around the EW scale. We have checked that the vacuum configuration proposed is indeed a minimum of the scalar potential. Moreover, the presence of ϕ is needful because it allows keeping Δ inert while $\tilde{\Delta}$ develops

a VEV and it provides their mixing. Thanks to this, the loop in Fig. 2 gives a no null contribution.

The gauged version of the model proposed is slightly less minimal but much more phenomenologically interesting: by requiring anomaly cancellation and neutrino masses preservation, we get a MeV sterile neutrino stable under a matter Z_2 symmetry that could be a good DM candidate. Moreover, the presence of the new gauge boson Z' and of the new neutral scalars below the TeV scale gives rise to testable and characteristic signatures at the LHC that may be studied in a following paper.

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